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HEAT TRANSFER MEASUREMENTS IN SMALL SCALE WIND TUNNELS

James R. Hayes

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This report describes an effort at the Flight Dynamics Directorate to use small scale models, miniature instrumentation, and small in-house hypersonic facilities to accomplish full configurational testing of vehicle concepts. The project included development of procedures for generating model geometry data and transmitting that data to 495th TW machine shops of model fabrication on NC machines. A discussion of problems peculiar to testing of small scale models is included. A comparison is presented of data taken under this effort with similar data taken in large production wind tunnels on large scale models.

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FOREWORD

This report represents the results of a study on the feasability of using small scale wind tunnels for obtaining heat transfer data normally obtained in large production facilities. The objective was to reduce the cost of configurational testing. The study was done under Laboratory Director's Fund Item, LDF N0. 84-05. Areas of interest were in model fabrication, instrumentation, and data reduction. The work was performed under Work Unit 24040773. This document is the final report for that work unit.

This technical report has been reviewed and approved.

List of Symbols

Symbol		Units
c	Specific heat	Btu/lb_m-R
D	Body diameter	in.
h	Heat transfer coefficient	Btu/ft^2-sec-R
k	Thermal conductivity	Btu/ft-sec-R
L	Thermal penetration depth	in.
L	Model reference length	in.
q	Heat flux	Btu/ft^2-sec
R	Cylinder radius	in.
t	Time	sec.
T	Model skin thickness	in.
T	Temperature	Deg. R
X,Y,Z	Model surface coordinates	in.
α	Angle of attack	Deg.
δ	Control surface deflection angle	Deg.
θ	Stability constant in 1-D reduction equation	
ρ	Density	lb_m/ft^3
ϕ	Circumferential angle (from top centerline)	Deg.

Subscripts

BF	Body Flap
cyl	Cylinder property
o	Stagnation condition
T_o	Evaluated at stagnation temperature

1.0 Introduction

This work unit was initiated as part of an effort to reduce escalating costs of wind tunnel testing. The primary objective of this effort was to explore the possibility of using in-house small scale research tunnels for configurational testing as an alternative to the large production tunnels at AEDC VKF. Several basic components of a wind tunnel test program were to be addressed. These included model fabrication, instrumentation, and data reduction techniques.

The fabrication of models used in the tunnels at the Flight Dynamics Directorate (FDD) has often been accomplished in the machine shops of the 4950th Test Wing. These models have traditionally been basic research configurations consisting of variations on flat plates, cones, and cylinders. Such geometries require only simple machining techniques. When this effort was initiated these shops were installing a CAD/CAM system which could allow the fabrication of more complex geometries representing real flight vehicles. Such a capability could allow small scale configurational testing to be accomplished completely in-house.

The first task of this work unit was to develop the necessary computer interfaces that would allow FDD to generate model geometry data compatible with this CAD/CAM system. This interface would then be used to fabricate a model.

Assuming that small scale configurational models could be made in-house, it is then necessary to develop suitable instrumentation for these models. Heat transfer instrumentation is the primary interest here. The small scale of the models would require a correspondingly small scale heat transfer gauge. In recent years the coaxial thermocouple has been developed as the the standard heat transfer gauge within FDD and these can now be obtained with diameters as small as 0.015 inch. The second task of this work unit was to evaluate the performance of this gage in a heat transfer gradient environment through numerical techniques. Suitable data reduction techniques would also be developed.

The third task was to instrument and test the model produced in Task 1 n the FDD Mach 6 facility and apply the data acquisition and reduction techniques of Task 2. In particular this task was to determine the magnitude of conduction errors expected as a result of the small scale, and to investigate ways of reducing these errors through improved gauge installation and data reduction techniques.

2.0 Model Fabrication (Task 1)

If the small scale research tunnels at FDD were to be used effectively for configurational testing, then the first task was to find a way to produce small geometrically complex models economically. From the begining of this effort, it was decided that all work would be done within WPAFB facilities to eliminate procurement lead times and reduce fabrication costs.

When this workunit was initiated, the machine shops at the 4950th Test Wing were installing a CAD/CAM system. It was obvious that this system had the potential to meet the model fabrication requirements of this effort; however, both FDD and 4950th TW personnel had to become familiar with the new system operation. The form, format, and quantity of data required for operating the

system was not initially clear to either group. Since this workunit was an LDF effort it was viewed as a perfect oportunity for the 4950th TW personnel to develop the necessary operating skills. The basic input data requirement was known to be an ASCII data file containing X,Y,Z surface coordinates. Since these would have to be provided by FDD, it was decided that FDD would proceed to generate the geometry data on FDD computers and establish communications between the FDD computers and the CAD/CAM computer. During this time the CAD/CAM group would become familiar with the procedures of converting a given surface data file into milling machine programs.

2.1 Geometry Generation Techniques

The configuration selected for modeling was the Space Shuttle. This vehicle was selected because an extensive data base exists as a result of the design testing carried out in several large production tunnels. This data base could be used as a quality standard against which data taken in this effort would be compared.

The first step to be taken in Task 1 was to develop methods of generating the surface coordinate data. The simplest technique is to generate the data files directly from 3-view and cross-section drawings on a digitizing tablet. The accuracy of this method, however, is less than desirable. The quantity of data required also makes this method tedious, especially if configurational changes are to be made. A more attractive approach is to use one of the geometry modeling codes developed for generating input data files for numerical flow field programs. At FDD the QUICK code (Ref. 1) has been developed for use with the AFWAL PNS code.

The QUICK code is a modularized system of interactive graphics programs which lead the user through the modeling process. The modeling process begins with rough cross-sectional data which can be obtained from a tablet using DIGIPLT software and cross-sectional drawings.
Curve fits of these data are then generated through the interactive graphics modules. The result is a well structured data file which describes the equations for a set of smoothly blended parametric surface patches covering the entire configuration. Each patch is defined by a set of four conic arcs that form its edges, and each conic arc is defined by the coordinates of three control points. These control point coordinates are the primary data contained in the geometry output file.

This method has several advantages. One is that the digitized cross-sectional data are smoothly blended over the modeled surfaces and are reduced to a compact format. The main advantage however is that configurational changes can be made easily through manual editing of the geometry output file. Configurational characteristics such as wing sweep, wing span, or control surface deflection can be changed by altering the coordinates of a few control points in the output file.
The complex modeling process is done only once for the basic configuration. An output module reads the geometry file and draws a three-dimensional wire-frame image at any user specified orientation. This module is used to examine the geometry file for modeling errors and to generate surface coordinate data files. The wire-frame mesh density is user specified and the coordinates of each mesh point can be output. These coordinates are output in cross-sectional sets which can be transported directly to the CAD/CAM system. Since the QUICK geometry file is a continuous surface definition these surface coordinates can be generated at any location requested by the CAD/CAM operators.

With this modeling system defined the digitization of shuttle cross-sectional drawings was initiated. Several sources of data were used; however, it became evident that a sufficient number of accurate cross sections for modeling complex areas like the canopy would be difficult to obtain. Two of the large scale (0.0175 scale) Space Shuttle models constructed by Rockwell Int. for design testing at AEDC VKF facilities were stored at FDD. It was decided to use these models as a source for detail data. The models were taken to the 4950th TW Quality Assurance group where a Cordax machine was used to measure surface coordinates at specified locations.

Data output from these inspection machines was initially in the form of printed coordinates which had to be retyped into the FDD computer. It was suggested to the 4950th TW that a direct data link between the Cordax and their CAD/CAM computer should be developed to eliminate this manual interface. Several advantages of such a link were recognized by the 4950th TW and they initiated a contract to establish it. This link now exists and data can be transmitted directly to the CAD/CAM system for processing.

2.2 CAD/CAM Data Format

With the modeling tools defined, a QUICK geometry file was generated for a 0.004 scale model of the Space Shuttle. This file could now be used to generate any data required by the CAD/CAM system. By this time the 4950th CAD/CAM group was familiar with the new computer system and could specify exact data format requirements for interfacing with FDD computers. Data were to be transmitted on a magnetic tape with the following characteristics:

9 Track Magnetic Tape
Unlabeled
800 BPI
7 bit ASCII code, Even parity.

The surface data are written to this tape in free format as cross-sectional sets of X,Y,Z coordinates,

$$\left\{\begin{matrix} X & Y & Z & \\ X & Y & Z & \\ \cdot & \cdot & \cdot & \\ \cdot & \cdot & \cdot & \\ \cdot & \cdot & \cdot & \\ X & Y & Z & A \end{matrix}\right\} 1st\ Cross\text{-}Section$$

$$\left\{\begin{matrix} X & Y & Z & \\ X & Y & Z & \\ \cdot & \cdot & \cdot & \\ \cdot & \cdot & \cdot & \\ \cdot & \cdot & \cdot & \\ X & Y & Z & A \end{matrix}\right\} 2nd\ Cross\text{-}Section$$

one set per line. The last record of each cross section ends with an "A" to indicate to the CAD/CAM system that this is the end of a crosssection. The X,Y,Z coordinates can be written to any desired accuracy but the CAD/CAM system is accurate to only 0.001 inch.

A tape containing the surface coordinates for the Shuttle geometry was written on the FDD computer and the data were read into the CAD/CAM system. The CAD/CAM interactive graphics utilities were used to divide the file into machinable subunits and milling machine programs were generated. A test piece was then machined from hardwood. If any part of the test piece required additional detail then the additional surface data were generated at FDD and added to the CAD/CAM data base. When each subunit of the model was reproduced satisfactorily the model was machined from 17-4PH stainless steel. Figures 1 and 2 are photographs of the model under construction and the finished model.

The computer links developed under this effort are illustrated in Figure 3 as a flow chart of the model generation process. The same geometry defined for use in numerical flow field codes can be sent to the tunnel as a test article.

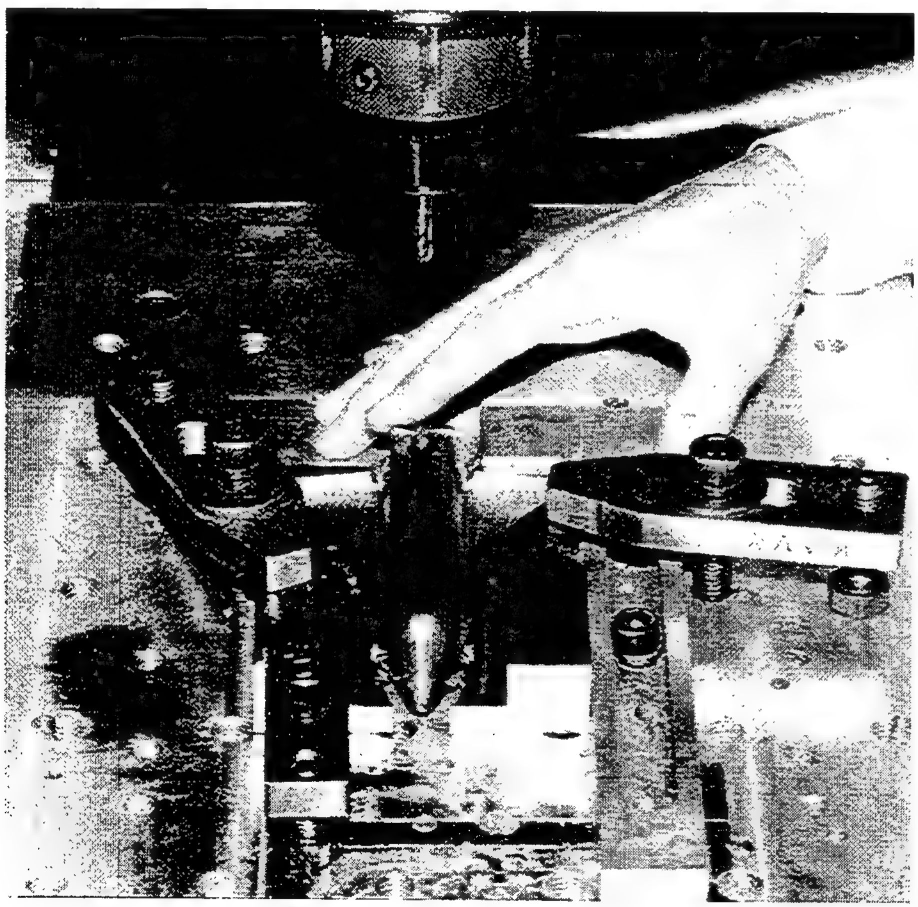


Figure 1 Model in first stages of fabrication on NC mill

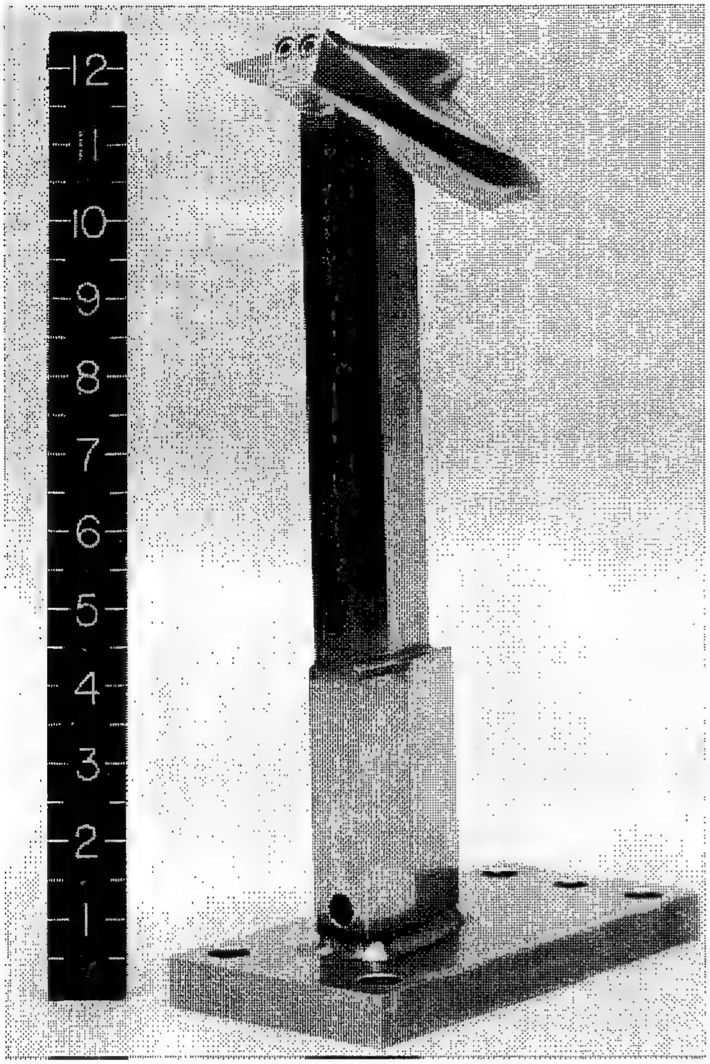


Figure 2a Finished model mounted on strut

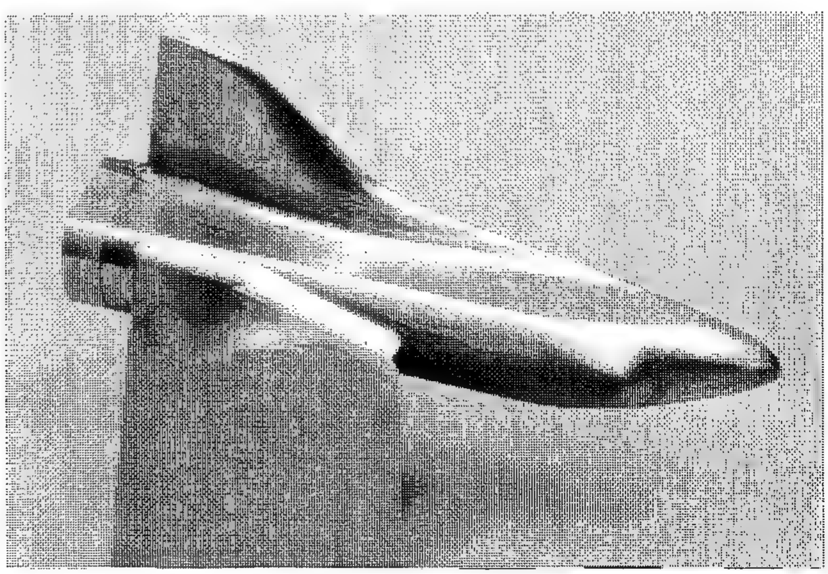


Figure 2b Closeup of model

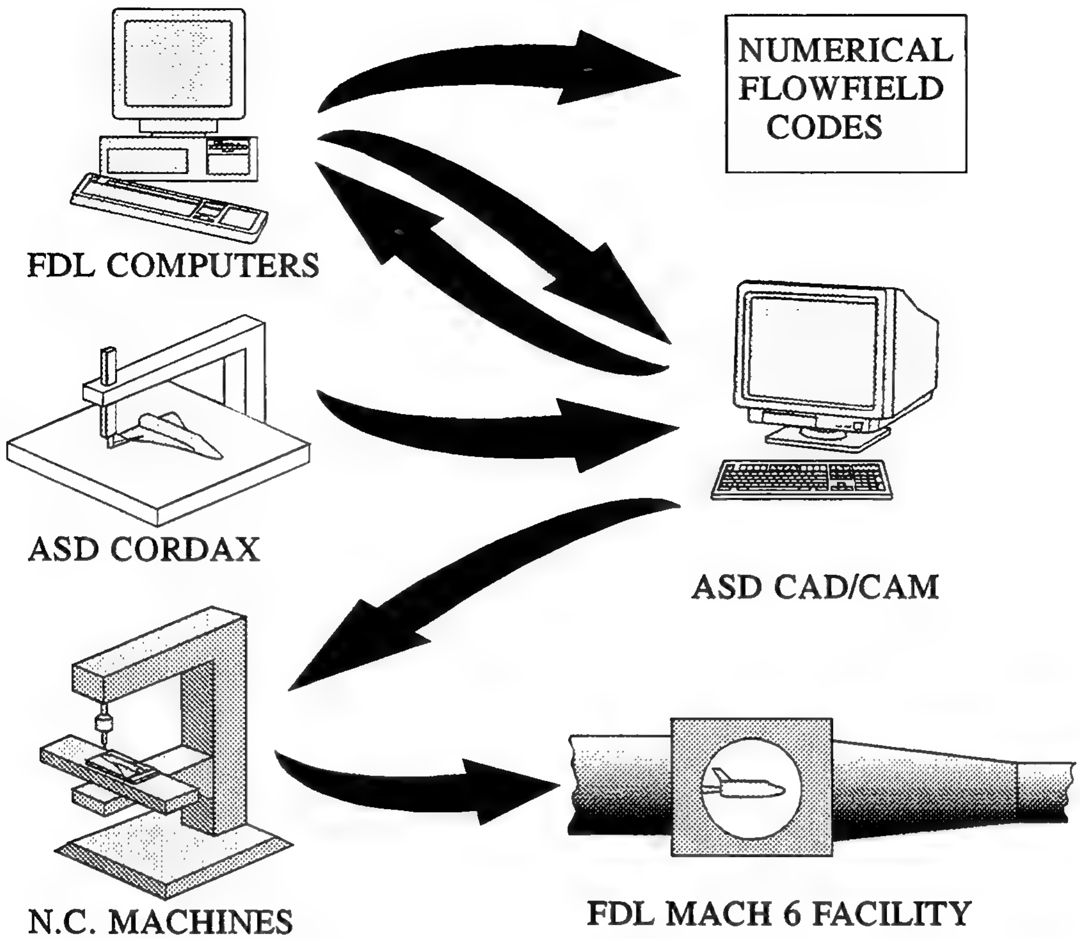


Figure 3 Data links developed under this effort

3.0 Instrumentation and Test Techniques (Task 2)

Instrumentation, data reduction, and test techniques are normally discussed as separate subjects but all are interrelated with respect to the quality and accuracy of heat transfer data. For this reason all three subjects will be addressed simultanieously here.

Small scale wind tunnels traditionally used for basic research present special heat transfer instrumentation problems when attempts are made to test full vehicle configurations. Basic research test programs are generally concerned with making measurements on variations of simple geometries such as flat plates, cones, spheres, and cylinders. Tunnels having test section diameters of approximately 8 to 12 inches can accommodate such models of sufficient scale to make detailed measurements of heat transfer distributions. More complex geometries which produce shock interactions produce very high localized heating regions. Peak heat transfer coefficients can only be measured in this type of flow field if the interaction region can be modeled in a scale which fills the test section.

As an example, the peak heating in the interaction region upstream of a cylinder on a flat plate is confined to a region less than one cylinder radius upstream of the cylinder face. This is illustrated in Figure 4. In this region the heat transfer coefficient increases by an order of magnitude as you approach the cylinder face. The actual peak is located at 0.2 radii upstream of the cylinder face. This may represent the flow field at the root of a blunt fin or wing. If the configuration being tested is a full vehicle then the test section restrictions on model scale will require the leading edge diame-

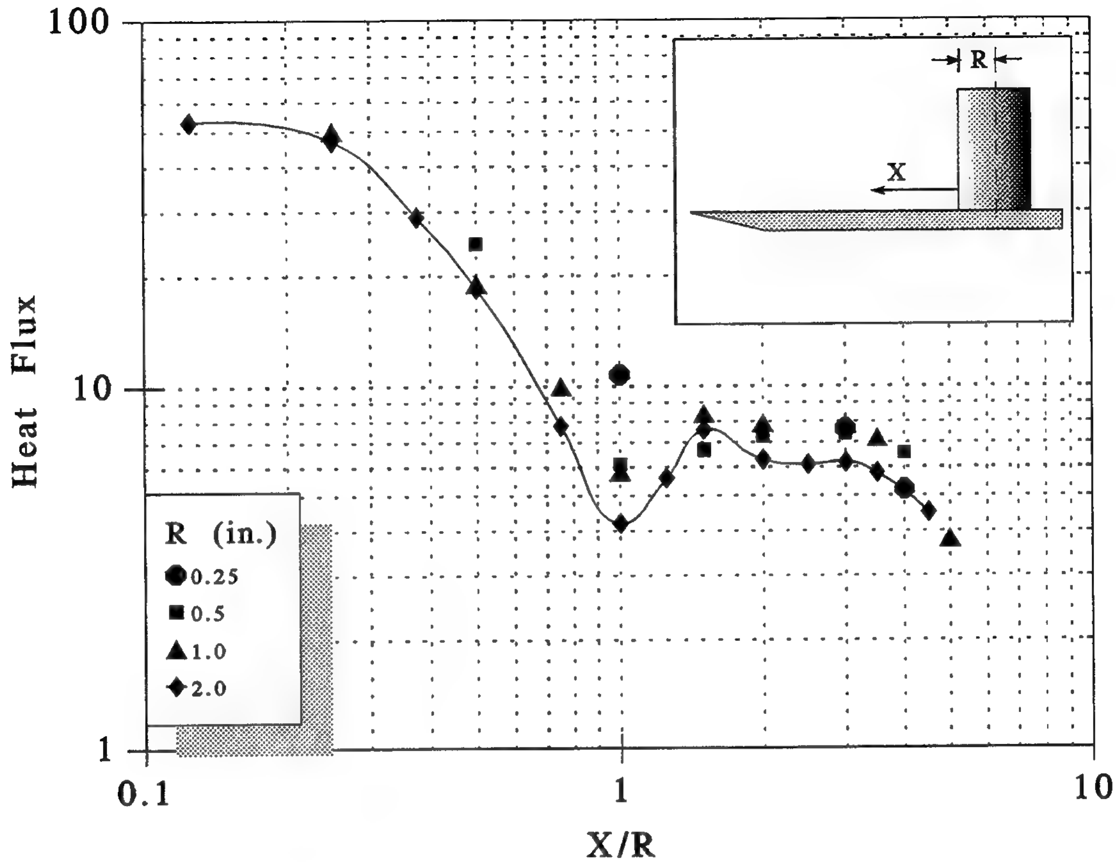


Figure 4 heating distribution upstream of a cylinder

ter to be about 0.1 inch. This means that the peak heating is located 0.01 inch from the fin root. Such a small region of peak heating will require an extremely small gauge to resolve the peak value.

Very small gauges may solve some of the dimensional problems of small scale testing; however, as noted above, within one gauge diameter, the heat transfer coefficient may change by an order of magnitude. Heat transfer gradients of this magnitude present another problem common to all methods of heat transfer measurement; that is lateral conduction errors. High aerodynamic heat transfer gradients produce high thermal gradients along the surface of the model as run time progresses. The thermal gradients in turn cause lateral conduction along the surface which drains heat from the peak locations and transfers it to regions of lower areodynamic heating. Since all gauges (not thermally isolated from the model structure) measure the sum of the aerodynamic and conduction heat transfer rates, the measurement of a highly localized peak is difficult because the heat you are trying to measure is being conducted away from the gauge.

An example of this effect was demonstrated in a comparison of test data taken on several similar finned ogive cylinder models of various scales. The first model was a thin skin thermocouple model

8" in diameter, 50" long, and had a skin thickness of 0.032". It was tested at Mach 6 in Tunnel B at AEDC and produced high quality heat transfer data in the fin interaction reagion. A 1/4 scale version of this model was also tested in the FDD Mach 6 facility. It also had thin skin thermocouples installed and a similar skin thickness of 0.030". Since Reynolds numbers in the FDD facility are high enough to match the length Reynolds number of the AEDC test and the instrumentation was small enough to resolve the scaled interaction region, it was expected that comparable test data could be obtained. Figure 5 shows that this was not the case. The scaled down interaction region produced much higher thermal gradients and lateral conduction in the relatively thick skin were excessive. A similar 1/4 scale model was tested at DFVLR in Gottingen, Germany. This model, however, had a skin thickness of 0.008". As shown in Figure 5 proper scaling of the skin thickness

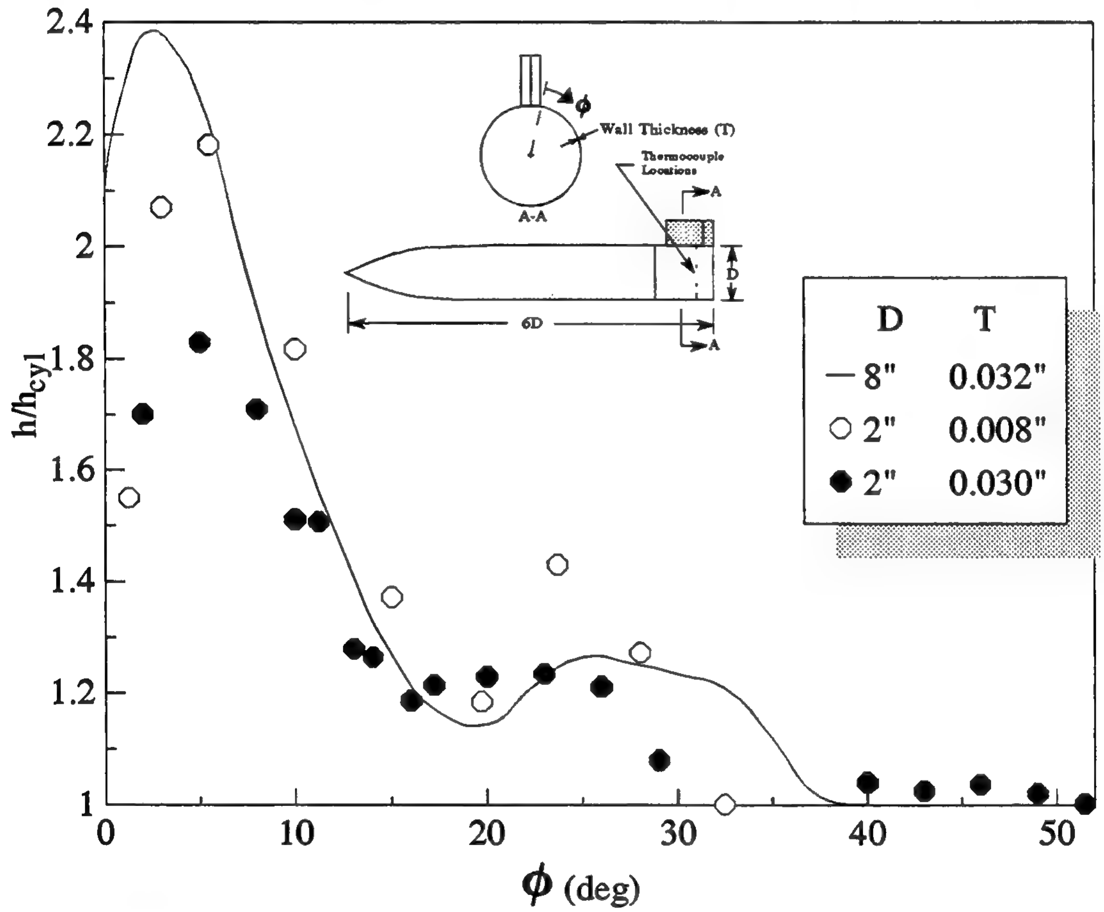


Figure 5 Conduction errors in small thinskin models

produced much better results. The only problem is that such a thin skin would be very difficult to produce in a more complex model having compound curvatures in the surface.

This problem has traditionally been attacked by using extremely thin skin models and attempting to take data at high speed. Measurements are taken early in the run before substantial thermal gradients are established. In a small high density tunnel this is often difficult because heating rates are so high that the thermal gradients are also established very quickly. Aerodynamic loads are also a problem on such thin-skin models. An alternative approach is to install an array of gauges in the peak heating region so that the lateral thermal gradients can be accounted for in the data reduction technique. This approach requires a large increase in the number of data channels required for a

particular measurement and the data reduction technique is complex. Also, small scale models are difficult to instrument in any dense pattern. If the isntrumentation and data reduction technique presupposes that the heat transfer coefficient at any point is constant (as thin skin techniques do) then one of these two methods must be used.

The coaxial thermocouple shown in Figure 6 is idealy suited for installation in a thick wall for which a semi-infinite slab or finite slab reduction technique can be formulated which allows a variable heat transfer coefficient to be measured. Under these conditions another approach can be used to measure very high localized heating. This method is to sweep the peak heating region across a single gauge during the run. Since the peak heating location is continuously moving along the surface, lateral temperature gradients are reduced. In the example of a cylinder on a flat plate, this may be done by driving the cylinder along the plate. A more accurate measurement of the peak heating is obtained and at the same time the continuous heating distribution through the region is obtained in one run and with one gauge.

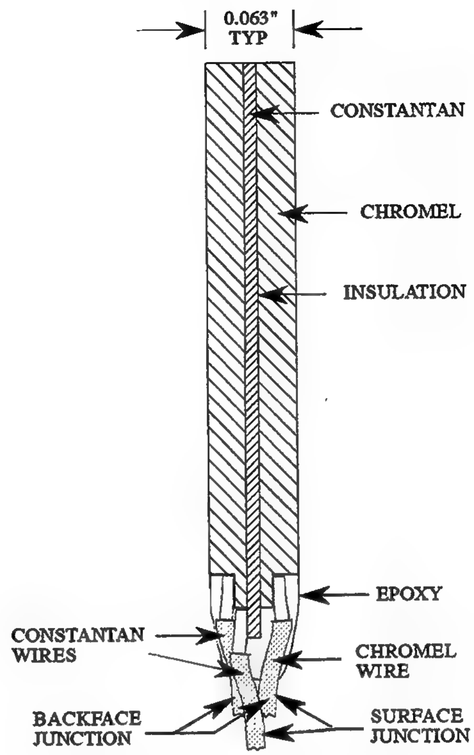


Figure 6 Standard Type E Coaxial Thermocouple

If the peak heating location is a function of the model orientation, then the model may be driven through a pitch sweep during the run. This has an added advantage of obtaining data at all angles of attack in a single run. This technique was demonstrated in an experiment in which the peak heating due to vortex impingement on the side of the space shuttle was measured in the NSWC Tunnel 9. The data are shown in Figure 7 and show the detail with which the peak level and its location with angle of attack may be mapped with relatively few gauges and in a single run.

A similar experiment was conducted in VKF Tunnel C in which the heating in the vicinity of the body flap of the Space Shuttle was examined. In this experiment the body flap was driven by an onboard motor so that it could be deflected during a run. Figure 8 presents an example of the data obtained at the hinge line and shows the onset of laminar separation with deflection angle as well as transition to turbulent unseparated flow. All data were obtained in a single run.

These "dynamic testing techniques" offer the most efficient means of generating a detailed data base using a minimum of gauges. In regions of high heat transfer gradient they further offer a means of reducing the lateral conduction errors. Both of these characteristics are important to the instrumentation of small scale models.

The coaxial thermocouple can be purchased with or without the backface junction. The gauge was initially produced with only the front face junction and data taken with that gauge were reduced

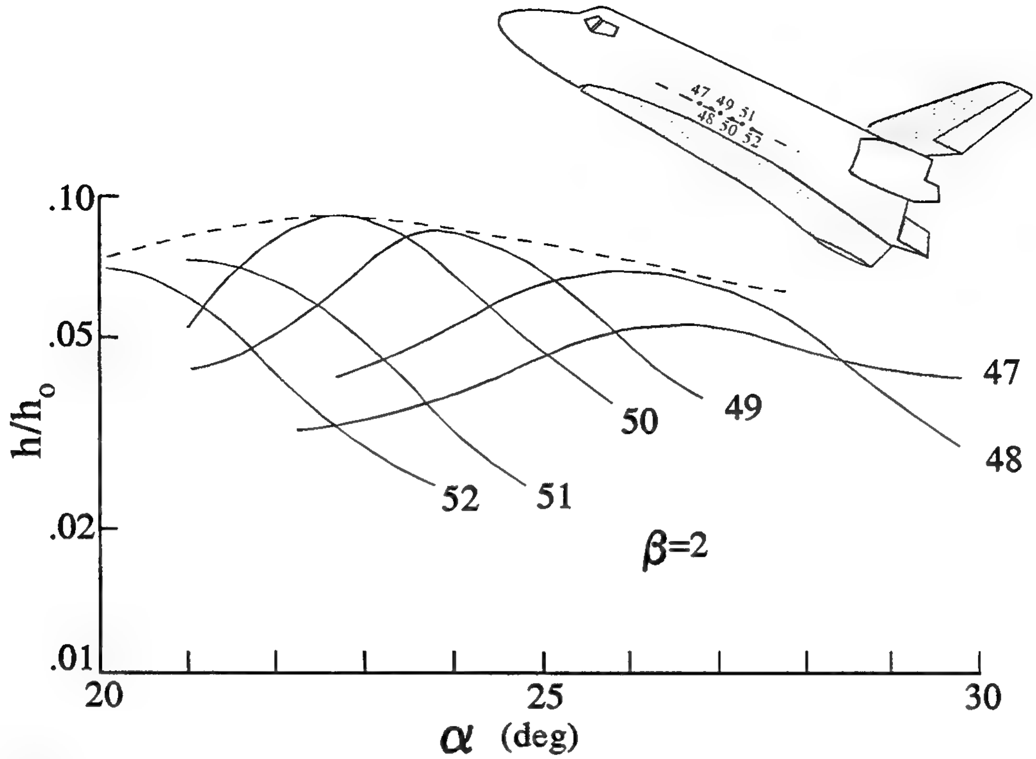


Figure 7 Vortex impingement peak heating obtained during pitch sweep

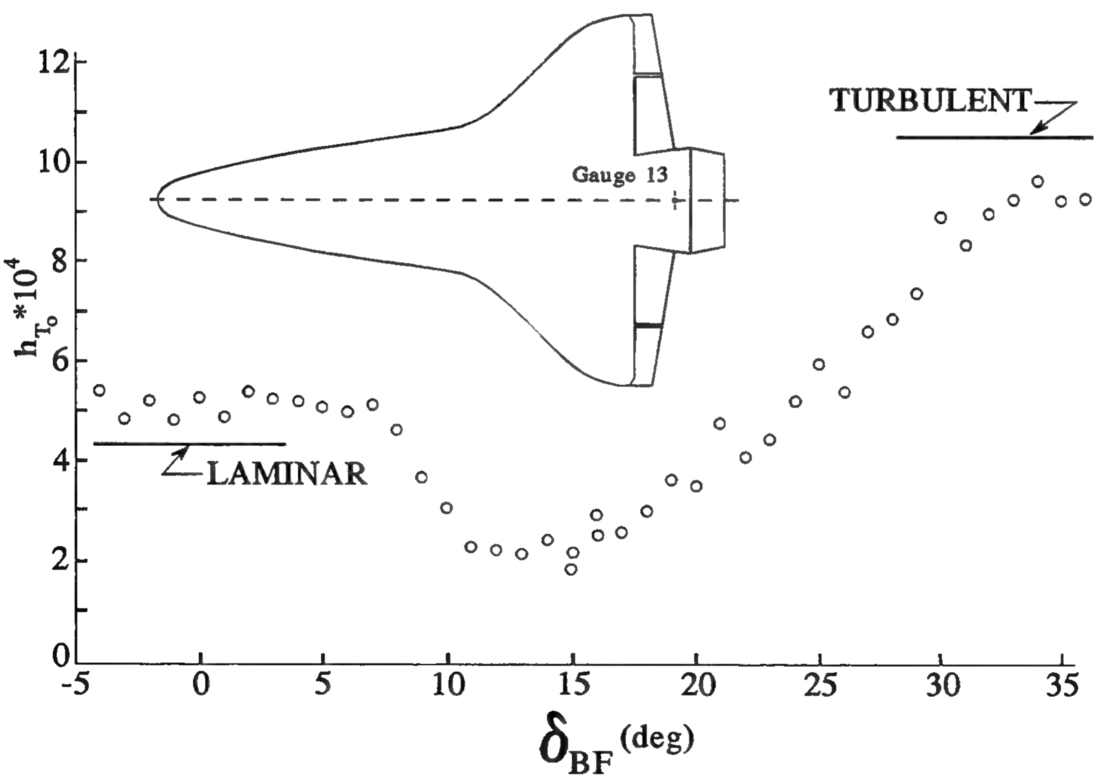


Figure 8 Heating at Gauge 13 during flap sweep

using a semi-infinite slab thermal model. With this technique the computed heat transfer rate is accurate only while the backface temperature remains at its initial value. Once the thermal pulse reaches the backface the wall no longer responds as a semi- infinite slab and the reduction equations are invalid. This time limit is given by

$$t_d = \frac{0.2\ L^2}{\alpha}$$

where α is the thermal diffusivity and L is the gauge length.

The addition of the backface junction on the gauge allows the use of a finite slab thermal model to be used. Reduction equations based on the finite slab thermal model use both front and back face temperature data and so remove the run time limit imposed by the semi-infinite slab assumption. Accurate heat transfer data have been taken with this technique for run times as long as 60 seconds. The run time is now limited only by the onset of lateral conduction. If heat transfer gradients in the vicinity of the gauge are mild then long run times are possible. The disadvantage of using gauges with backface junctions is that the number of data channels required for a given number of gauges is doubled.

The data reduction equations are derived by starting with the heat equation for one dimensional flow given by

$$\frac{\partial T}{\partial t} = \frac{k}{\rho c} \frac{\partial^2 T}{\partial x^2}$$

A forward time and central spaced explicit difference method is applied to this equation.

$$\frac{T_{n+1,i} - T_{n,i}}{\Delta t} = \frac{k}{\rho c} \frac{T_{n,i+1} - 2T_{n,i} + T_{n,i-1}}{(\Delta x)^2}$$

Solving for T_{n+1} results in

$$T_{n+1,i} = \theta[T_{n,i-1} + T_{n,i+1} + (1/\theta\ -\ 2)T_{n,i}]$$

where

$$\theta = \frac{k \Delta t}{\rho c (\Delta x)^2}$$

The boundary conditions imposed are that the temperature of the outer wall (i=1) is set equal to the frontface gauge temperature data and the inner wall temperature ($i=i_{max}$) is set equal to the gauge backface temperature data. Approximately 20 internal nodes are required for a gauge which is 0.4 inch long .

An important restriction is that the stability constant, θ, must be less than 0.5 for the solution procedure to be numerically stable. This means that if the data sample rate is so that θ is greater than 0.5 then the time step must be divided into a sufficient number of subintervals such that the stability condition is satisfied. The temperature data from the coax gauge is assumed to be linear between data samples (i.e. over the subintervals).

The heating rate is then computed from

$$\dot{q}_n = \frac{-k}{\Delta x}[4T_{n,2} - 3T_{n,1} - T_{n,3}]$$

This reduction technique may be used with no time restrictions since it correctly models the finite slab conduction process. It is also considerably faster than the semi-infinite slab algorithm.

An attempt has been made to use this algorithm with only frontface data and the results have been good. In this technique the temperature of the backface node (at $i=i_{max}$) is updated by setting it equal to the computed temperature at the last internal node ($i=i_{max}-1$). This is possible because the surface heating rate is a much weaker function of the backface temperature than it is of the frontface temperature and dT/dt at the backface nodes is very small. Extrapolation could be used but it does not seem to be necessary. This allows single junction gauges to be used for times much longer than the semi-infinite slab assumption would allow.

A fortran data reduction program which implements the finite slab data reduction technique as a subroutine can easily be written. The subroutine should be called with the gauge temperature history and would return the aerodynamic heat transfer rate history. The argument list would also include a switch to tell whether backface temperature data are to be used or whether values should be computed along with the heating rate.

The data reduction techniques described above are based on the assumption that the convective heating at the surface is conducted into the model wall one-dimensionally and along the axis of the coaxial gauge. Care must be taken in the design of the model to assure that this condition is maintained at least for the expected duration of a test run. The instrumented components of the model must be designed so that changes in wall thickness and component joints are thermally far from the gauge. The equation given earlier for the thermal diffusion time can be used to judge what this distance should be. The surface contour of the model must also be considered. Small surface radii promote heat transfer gradients which, in turn ,develop lateral thermal gradients in the vicinity of the gauge and produce multidimensional conduction in the model wall. Examples of this effect are discussed in Reference 2. The thermal properties of the material from which the model is to be constructed must also be matched with the type of coaxial gauge selected. Thermal property mismatch will also promote multi-dimensional conduction near the gauge. Different materials will store and conduct heat at different rates resulting in the gauge not being at the same temperature as the surrounding wall. The coaxial gauge used most often is constructed of chromel-constantan (Type-E) thermocouple materials. It is best matched with 17-4PH stainless steel. This steel can be machined easily in the annealed state and can also be heat treated to withstand extremely high loads making it ideal for fabricating wind tunnel models.

4.0 Wind Tunnel Test (Task 3)

4.1 The 0.004 Scale Space Shuttle Model

Task 3 of this effort was to instrument the model fabricated in Task 1 with the instrumentation developed in Task 2 and conduct a wind tunnel test. During the model design effort, an attempt was made to keep the small scale model design as simple as possible. Instrumentation was to include only the lower surface center line and the body flap. The duplication of standard large scale multi-component models in such a small scale was not desired from either an economic or an engineering viewpoint. The standard coaxial gauge shown in Figure 6 is installed by drilling a 0.063 inch diameter hole through the model wall and glueing the gauge in place. The gauge can be installed from either the inner or outer side of the model wall. Initial discussions with the gauge manufacturer led us to believe that this was true also for the miniature coaxial gauges. The model was therefore designed and fabricated in one piece and core drilled from the rear along its axial center line. A series of 0.015 inch diameter holes were then drilled along the lower surface center line into the core cavity. The gauges would be installed from the outer side of the model. When the gauges were received it was found that this was not going to be possible. As shown in Figure 9 the epoxy bead reinforcing the wire leads was much larger than the gauge diameter. This made installation of the gauges in the lower surface center line impossible as the model was designed and modification would be difficult. It was decided to instrument the body flap only and proceed with the test with the reduced instrumentation. The body flap was a separate piece and three thermocouples could be installed along the centerline and from the inside of the part. A fourth thermocouple was able to be installed in the shuttle fuselage just upstream of the flap hingeline location. The locations are shown in Figure 10. Four body flap modules were fabricated having deflection angles of 0, 5, 10 and 15 degrees. The model was welded to a strut in an inverted possition and at 20 degrees angle of attack. The wind tunnel pitch sector limit was 20 degrees so the model could be tested at angles of attack varying from 0 to 40 degrees.

4.2 Test Conditions

The wind tunnel test was conducted in the FDD Mach 6 High Reynolds facility (Ref. 3). This tunnel operates at a stagnation temperature of 1100 degrees Rankin and stagnation pressures of 800 to 2000 psia. For each body flap deflection, runs were made at angles of attack of 20, 25, 30, 35 and 40 degrees. This sequence was repeated for stagnation pressures of 800, 1200, 1600 and 2000 psia. Additional runs were made at selected body flap angles and stagnation pressures in which the model was driven through a pitch sweep of 20 to 40 degress. During this test some problems with the pitch sector controller resulted in sweeps which ranged from 0 to 40 degrees. The stagnation pressures selected for this test produced the following free stream length Reynolds numbers at the body flap hinge line:

Po :	800	1200	1600	2000
Re :	4.65	7.00	9.31	11.6 * 10

Two test entries were made. For the first entry no trip devices were installed because transition was expected to occur upstream of the hinge line within the Reynolds number range. For the second entry a grit strip was installed on the nose to ensure fully turbulent flow at all Reynolds numbers.

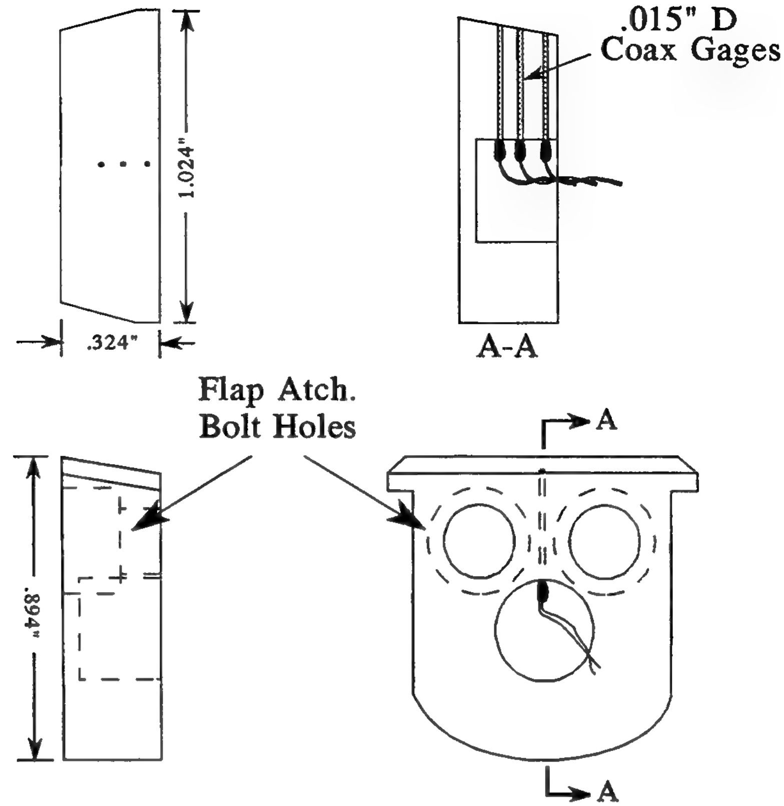
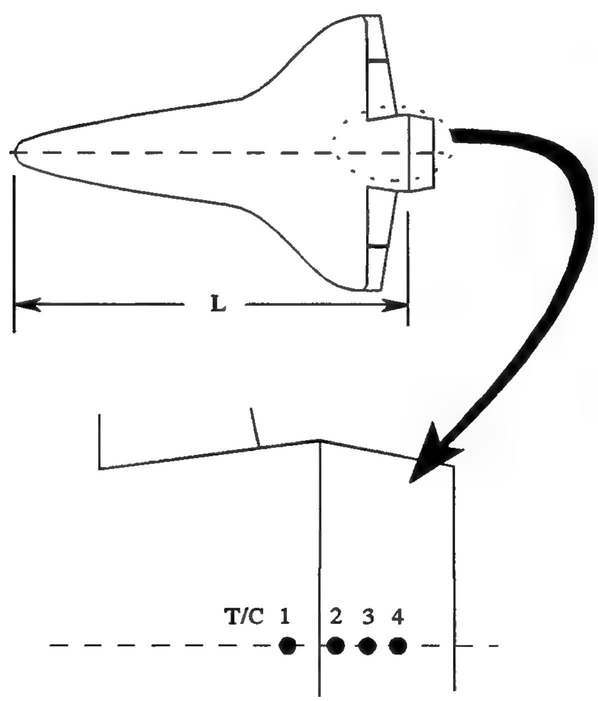


Figure 9 Instrumented flap design



L=5.173"

T/C	X/L
1	0.980
2	1.007
3	1.022
4	1.036

Figure 10 Instrumentation locations

4.3 Test Results

The test data from the first entry could not be confidently correlated as a whole. The high Reynolds number data appeared to be turbulent but the lower Reynolds number data appeared to be either laminar, transitional, or separated at various flap angles and model angles of attack. During each model injection the model was pitched from 20 to 40 degrees angle of attack and back to 20. On many of these runs significantly different heating rates were obtained on the up-sweep that were observed on the down-sweep. It was not clear whether this was lateral conduction errors or changes in the boundary layer state resulting from elevated model temperatures late in the run. If transition was occurring very near the flap hingline, then small changes in its location could also determine whether or not separation would occur at a given flap angle. The very limited number of thermocouples installed on the model did not provide sufficient upstream history to answer these questions. For this reason a second test entry was made in which a grit strip was applied to the nose of the model to ensure that fully turbulent flow occurred over the instrumented section at all test conditions.

A typical sample of the test data taken on the second test entry is shown in Figures 11, 12, and 13. Figure 11 shows temperature-time histories for each gauge. Figure 12 shows reduced heat transfer coefficients, and Figure 13 shows the heat transfer coefficients as a function of angle of attack. The latter plots show that the heating rates are now the same on both the up and down sweeps. This indicates that transition was occurring at the hingline on the first entry and was the cause of most of the confusing variations in heating rates. This sensitivity to small variations in transition location will be inherent to very small scale models.

The tripped test data were normalized by the turbulent sonic point heat transfer coefficient. If the data are fully turbulent then this normalization should make it independent of Reynolds number. A sample of the data is shown in Figure 14 for the 10 degree flap deflection. In this figure each test point contains four data points representing the four test Reynolds numbers. The correlation is very good indicating that the data are, in fact, turbulent. Figures 15a through 15d present the data for both the tripped and untripped conditions in the form of Stanton number versus Reynolds number plots. The solid lines on these plots are 1/5 slope data fairings of the tripped data. A 1/5 slope on this type plot is again indicative of turbulent flow. The departure from turbulent flow of the untripped data at low Reynolds numbers can be seen.

The data were also compared to test data taken on large scale models at Arnold Engineering Development Center in the VKF Tunnel B at Mach 8. An example is shown in Figure 16. The solid and dashed lines are the Mach 8 data taken with trips at various locations on the model. The data are plotted as a function of X/L where L is the length of the model measured from the nose to the body flap hinge line. Both tripped and untripped data are shown as symbols for the small scale Mach 6 test. The open symbols are data reduced with the standard one-dimensional finite slab heat conduction model described in Section 3.0. Correlation with the Mach 8 data is poor. Referring to Figure 9, the holes for the cap screws which attached the flap to the model are very close to the thermocouples. As a result of these holes, the heat conduction at the thermocouples was probably not one-dimensioal. The configuration was modeled with a two-dimensional finite element heat conduction code called TOPAZ (Ref. 4) and the data were reduced using the two-dimensional inverse code IHCP2D (also Ref. 4). The results are shown in Figure 16 as the filled symbols. It can be seen that the correlation of the tripped data with the Mach 8 data tripped at the nose is very good.

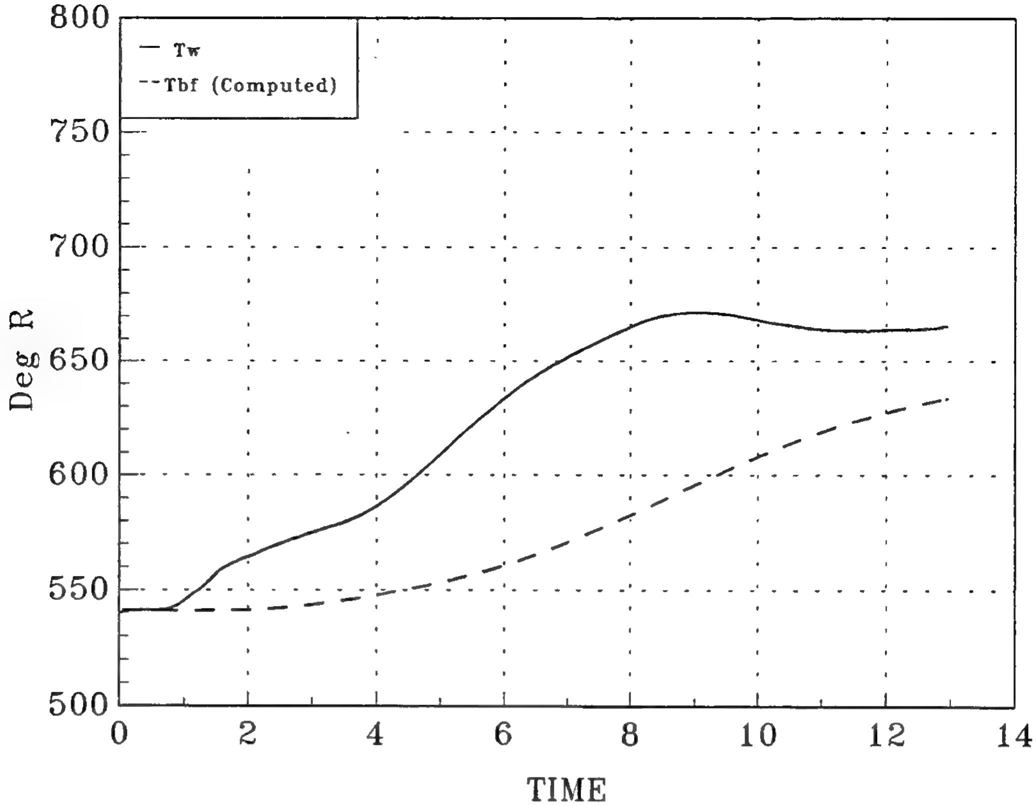


Figure 11a Typical temperature vs. time data for Gauge 1

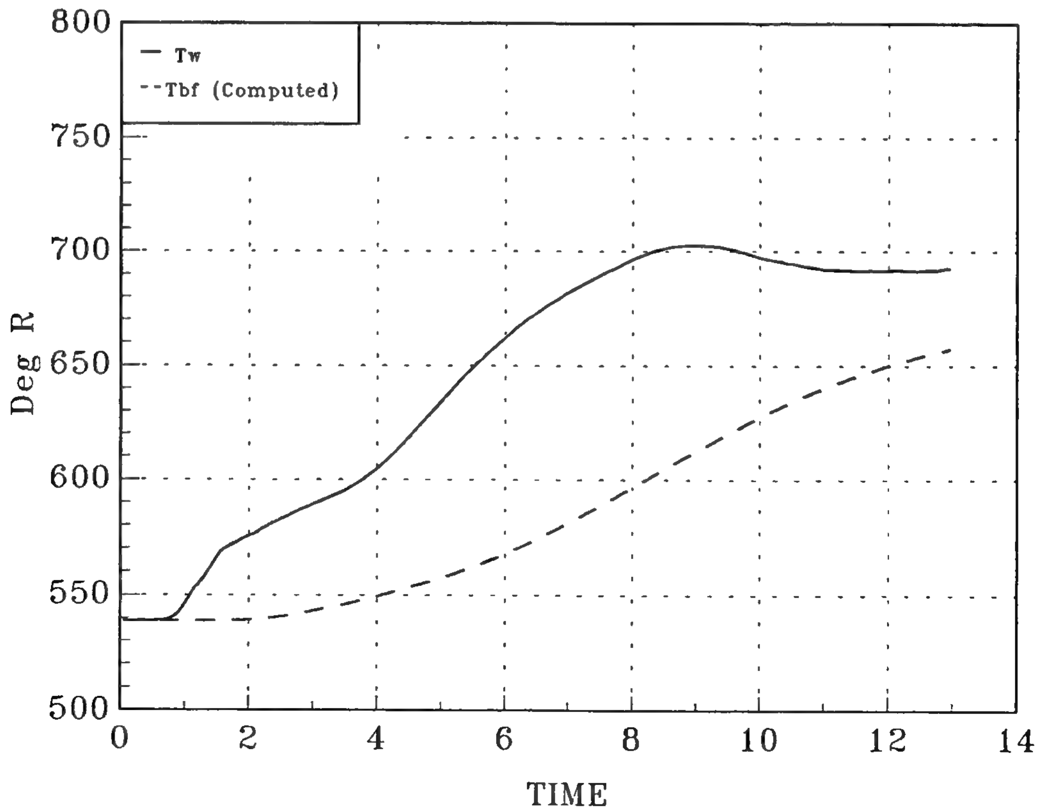


Figure 11b Typical temperature vs. time data for Gauge 2

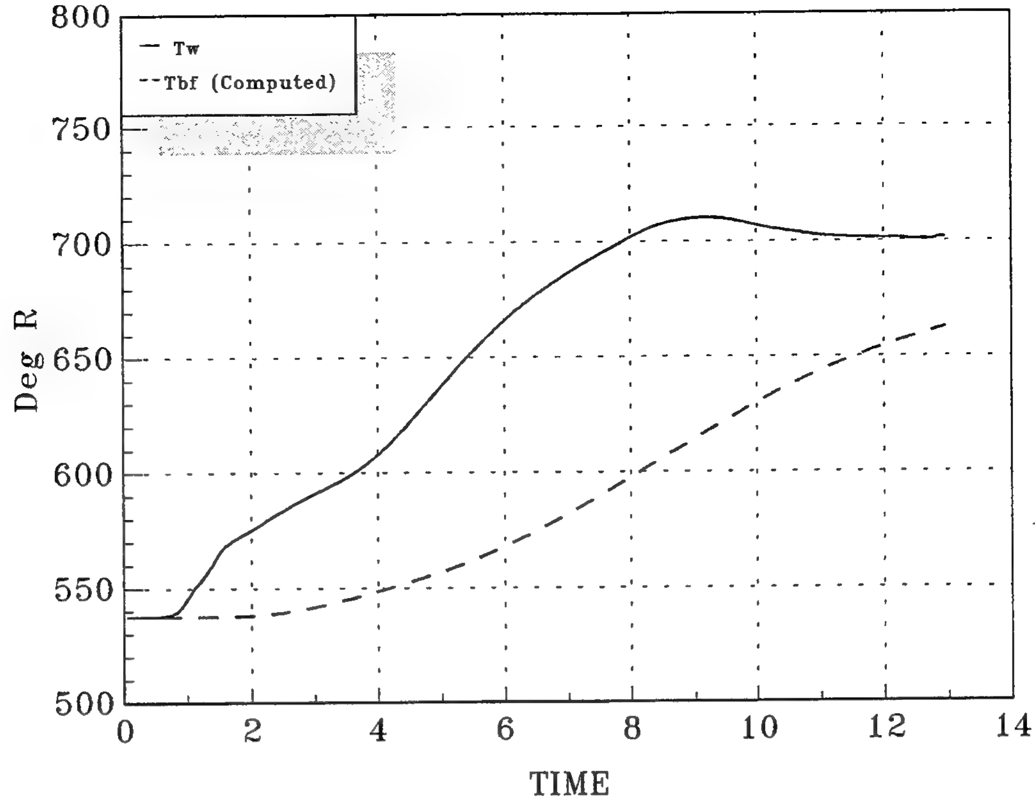


Figure 11c Typical temperature vs. time data for Gauge 3

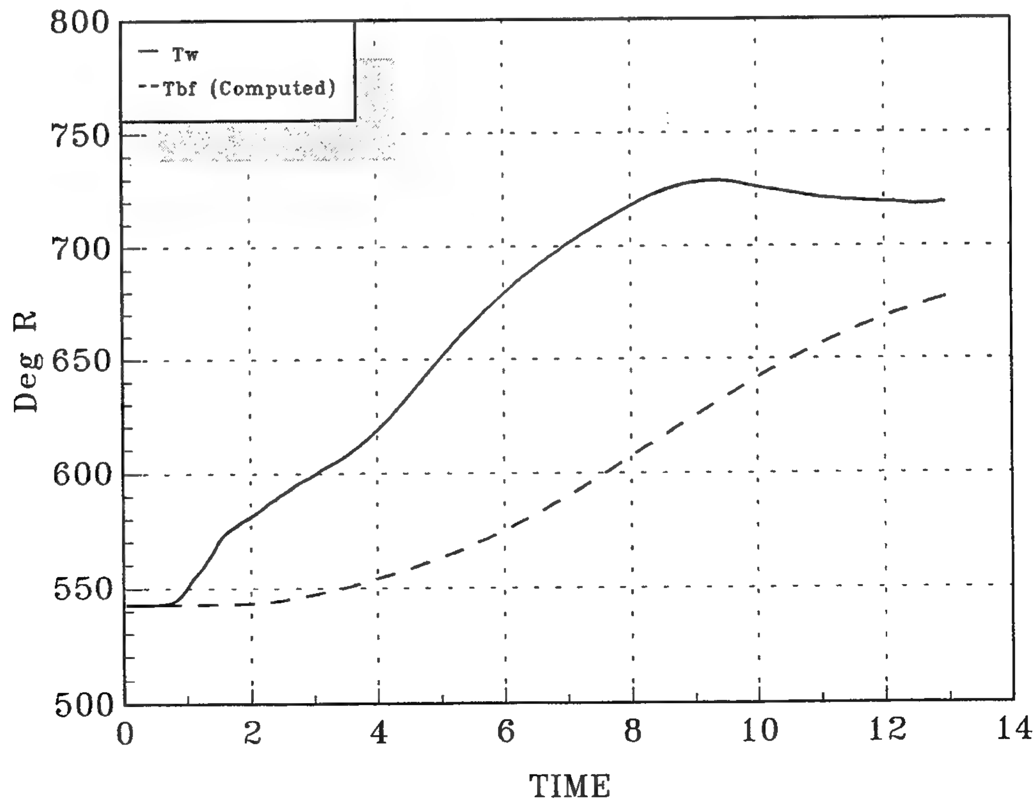


Figure 11d Typical temperature vs. time data for Gauge 4

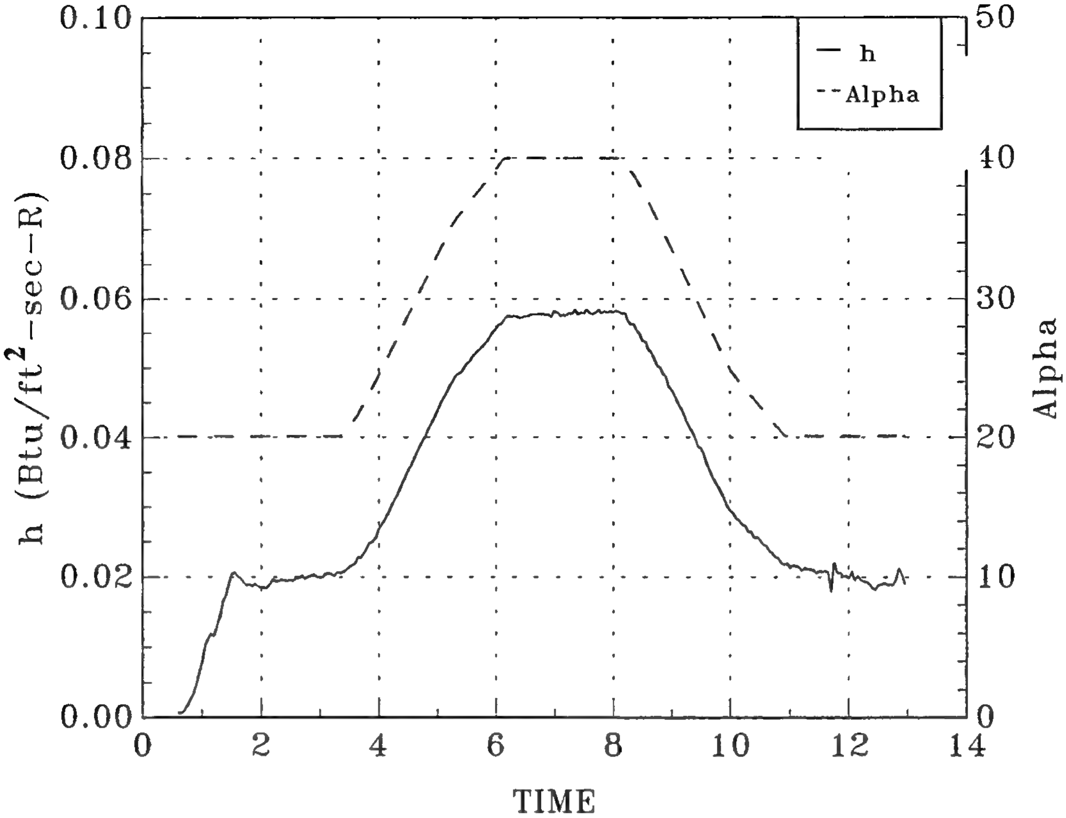


Figure 12a Typical heat transfer vs. time for Gauge 1

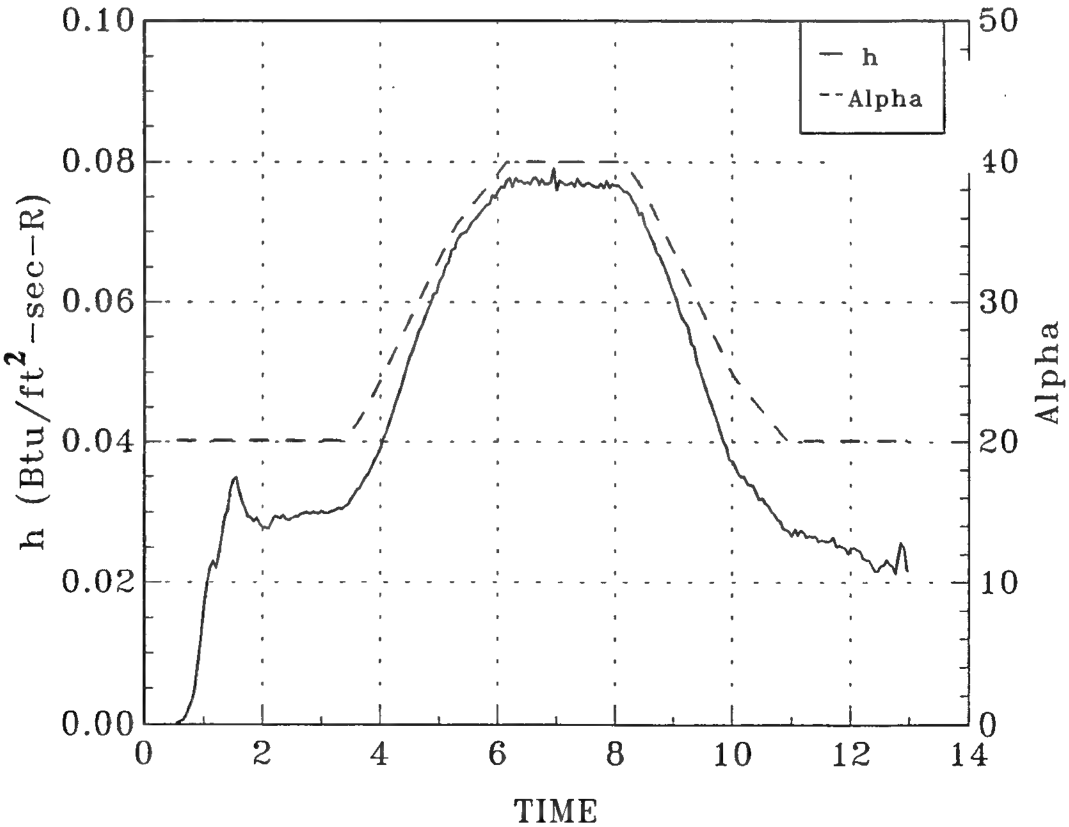


Figure 12b Typical heat transfer vs. time for Gauge 2

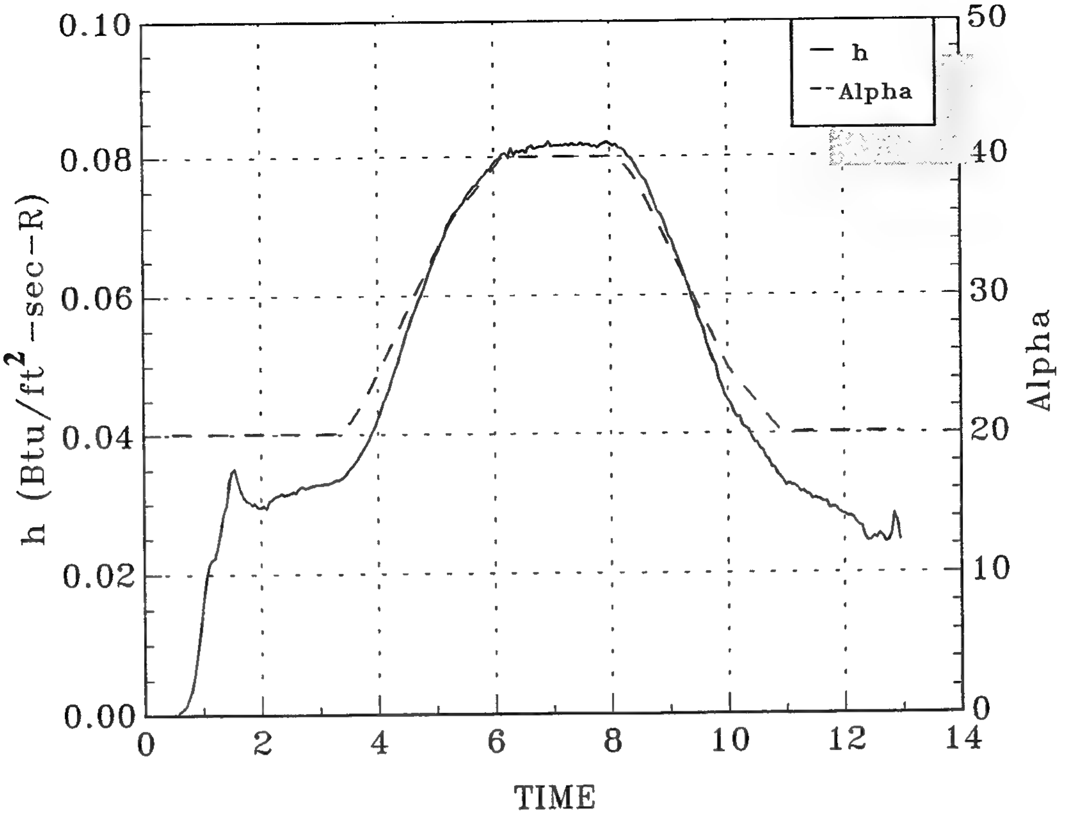


Figure 12c Typical heat transfer vs. time data for Gauge 3

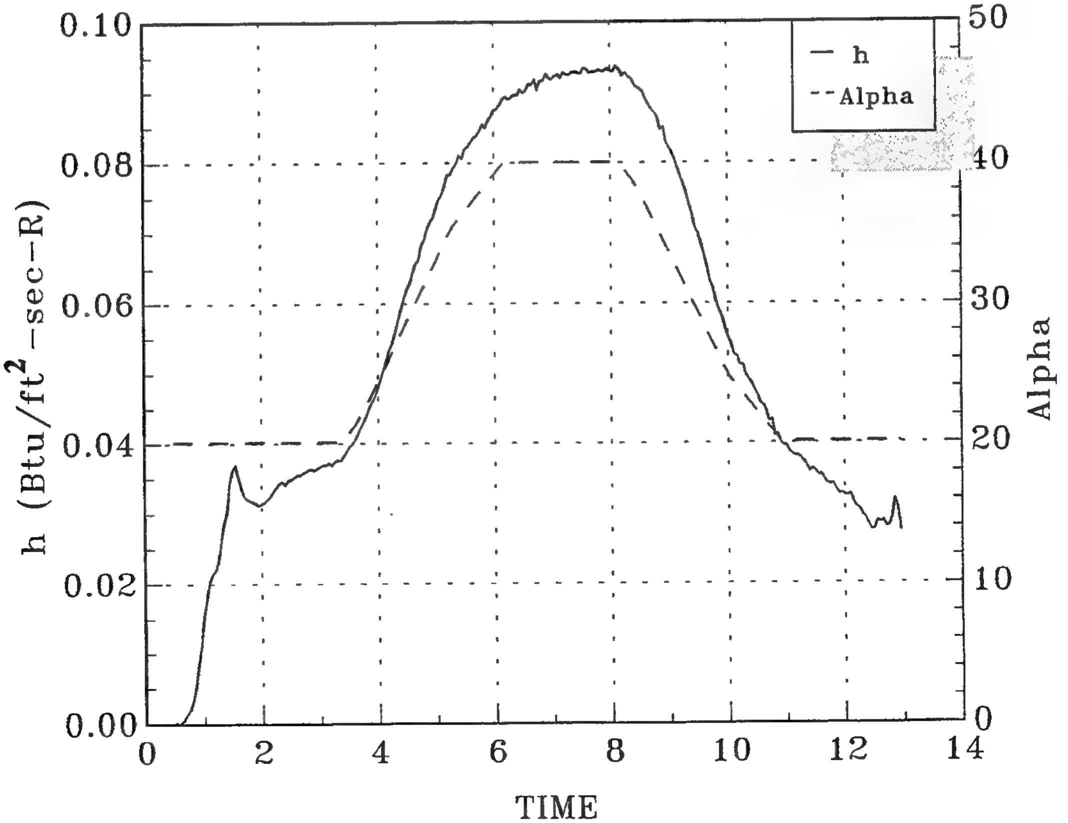


Figure 12d Typical heat transfer vs. time data for Gauge 4

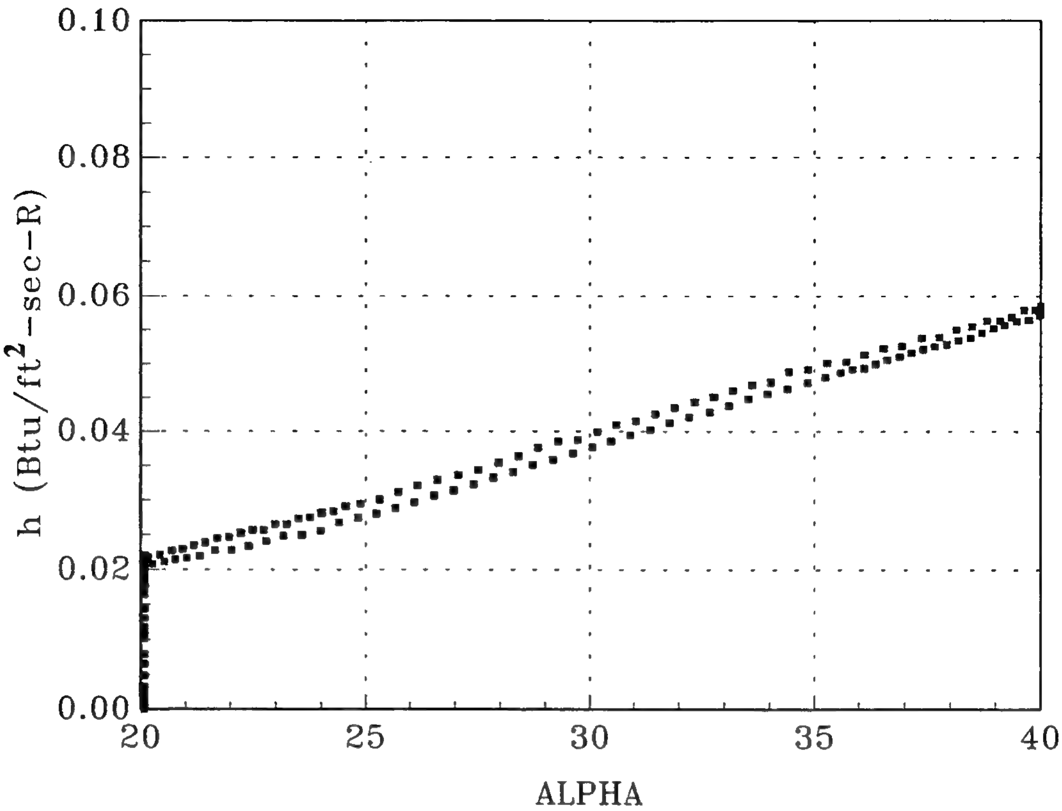


Figure 13a Typical heat transfer vs. alpha data for Gauge 1

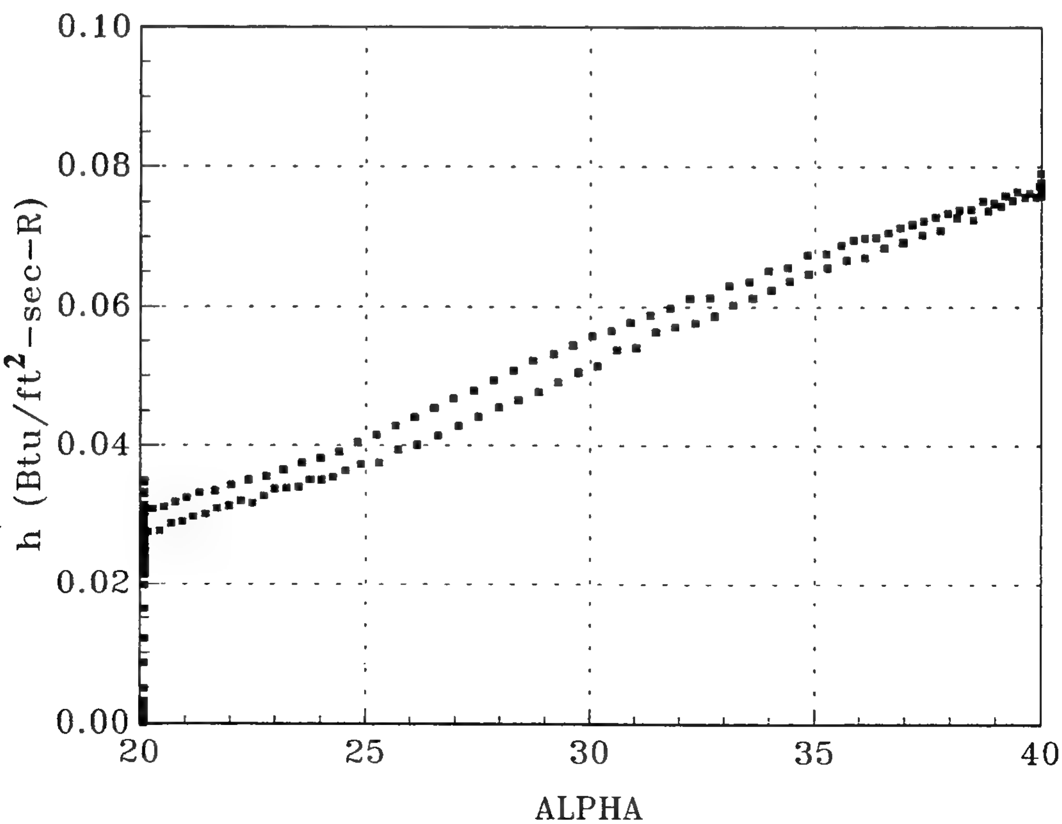


Figure 13b Typical heat transfer vs. alpha data for Gauge 2

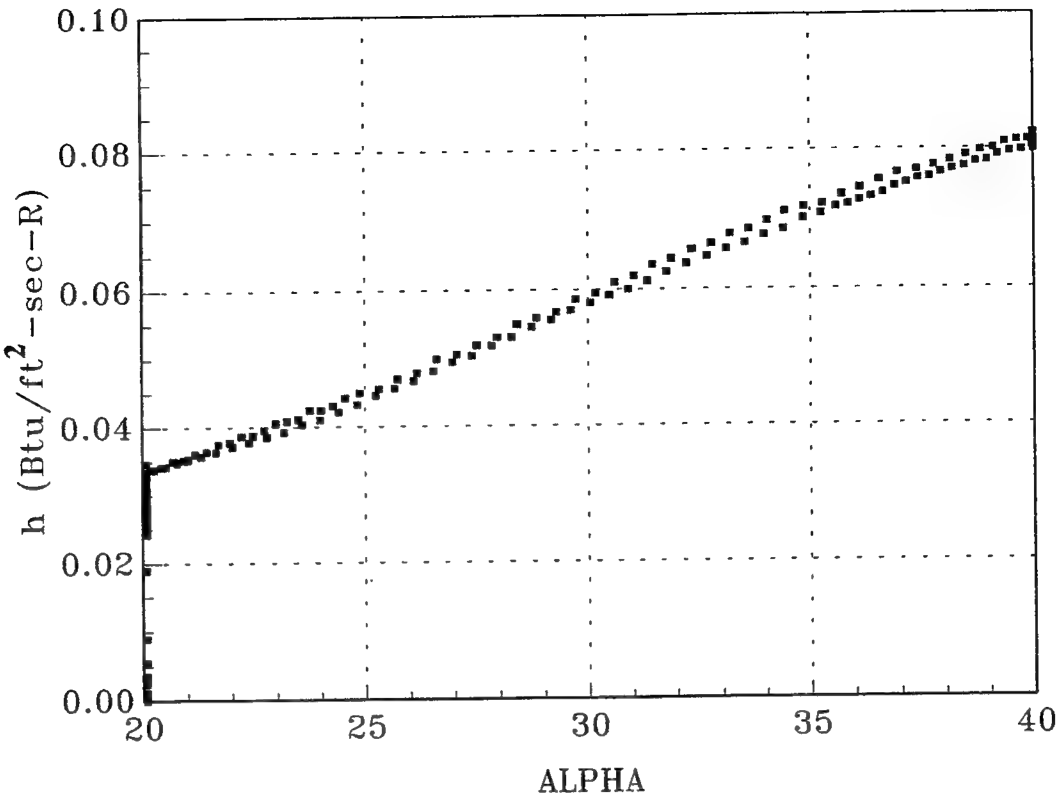


Figure 13c Typical heat transfer vs. alpha data for Gauge 3

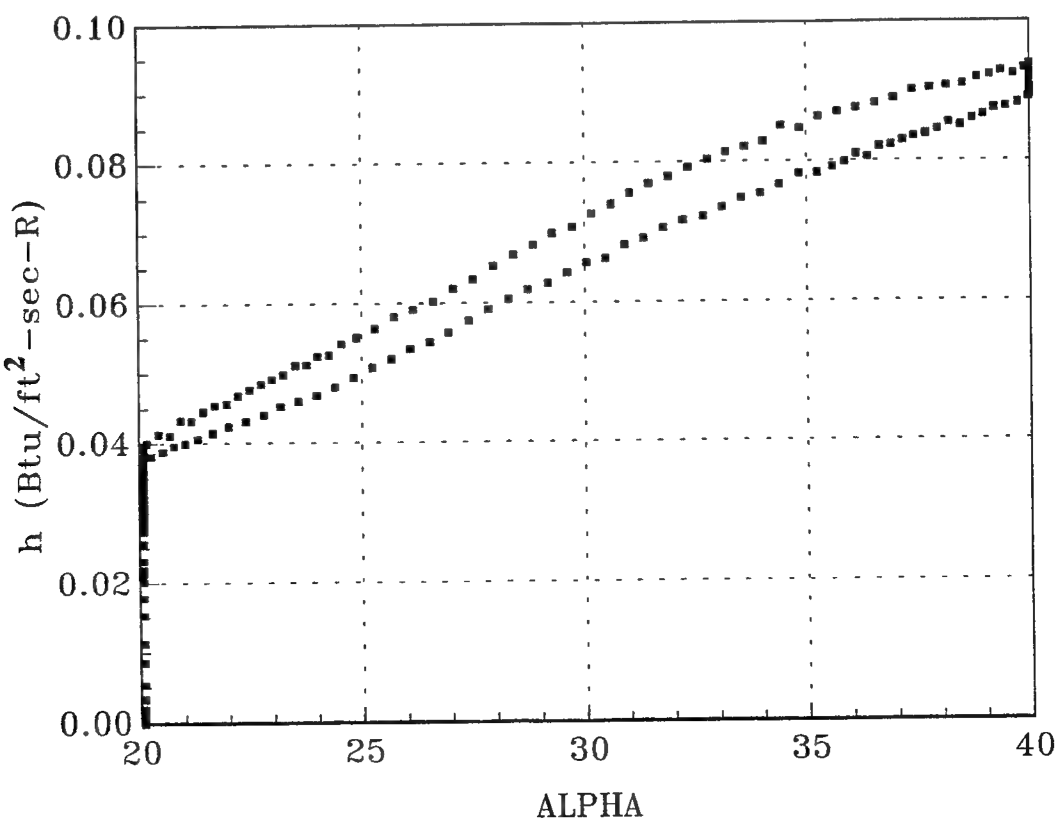


Figure 13d Typical heat transfer vs. alpha data for Gauge 4

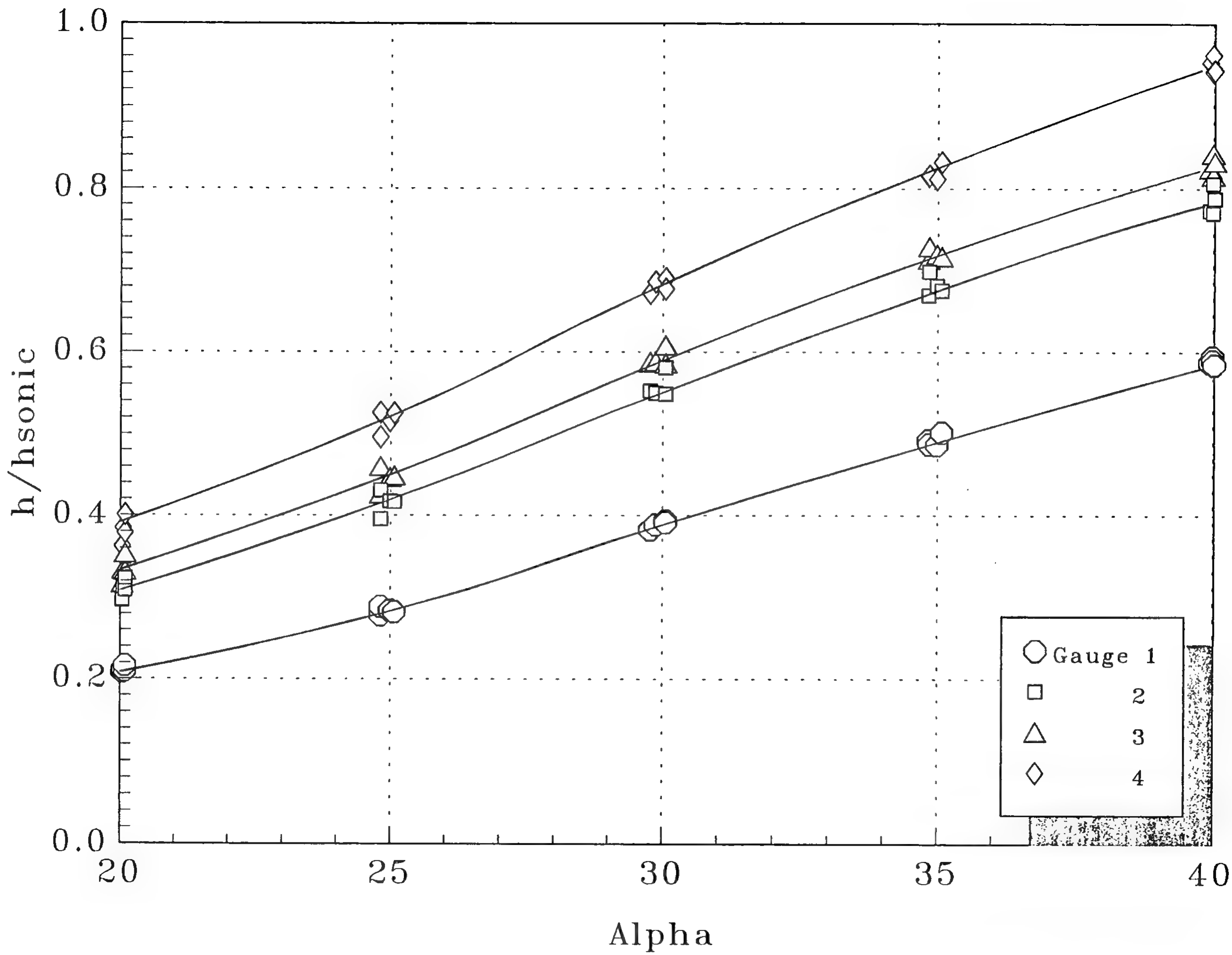


Figure 14 Turbulent correlation of tripped data

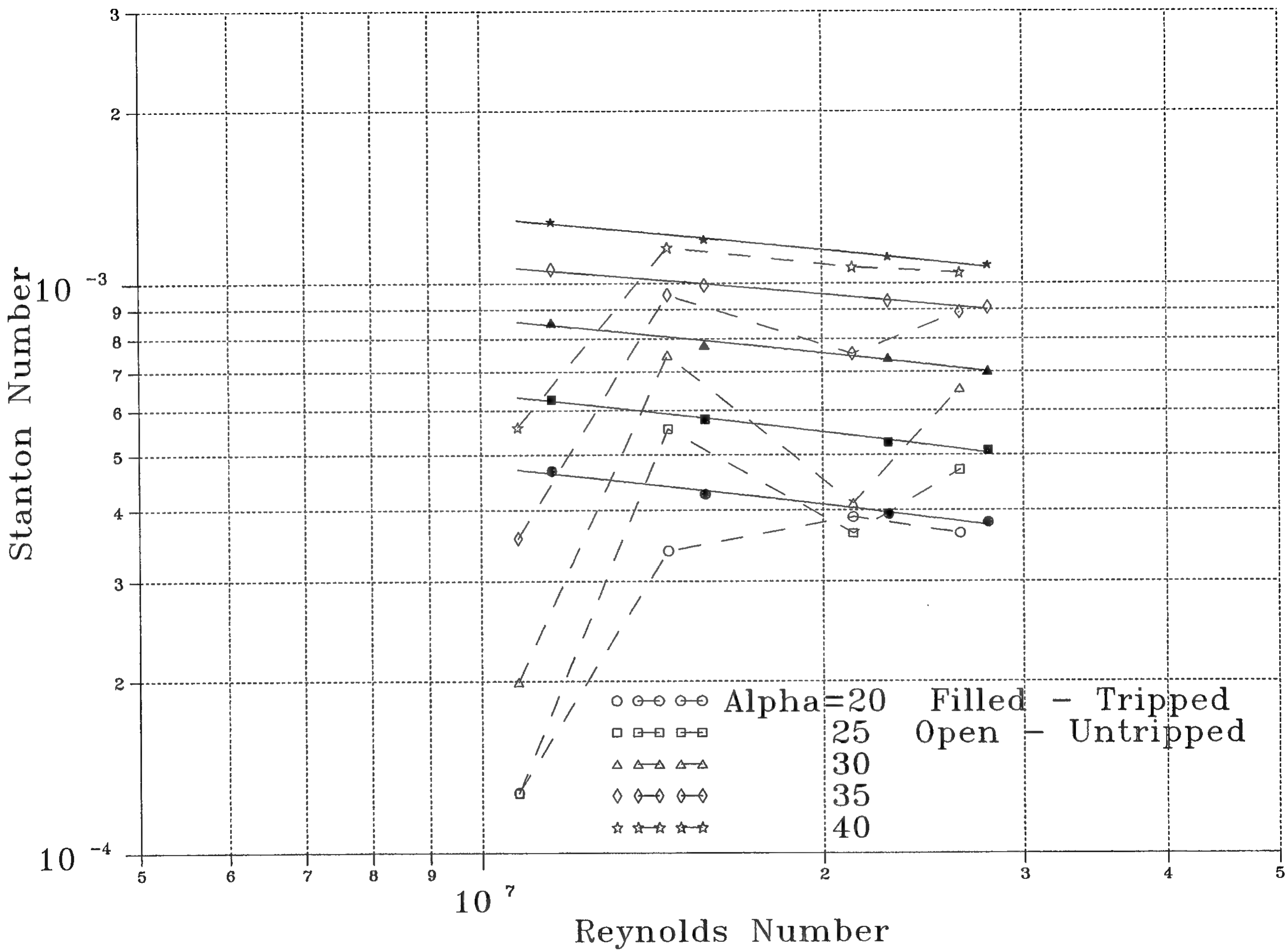


Figure 15a Stanton vs. Reynolds number correlation for Gauge 1

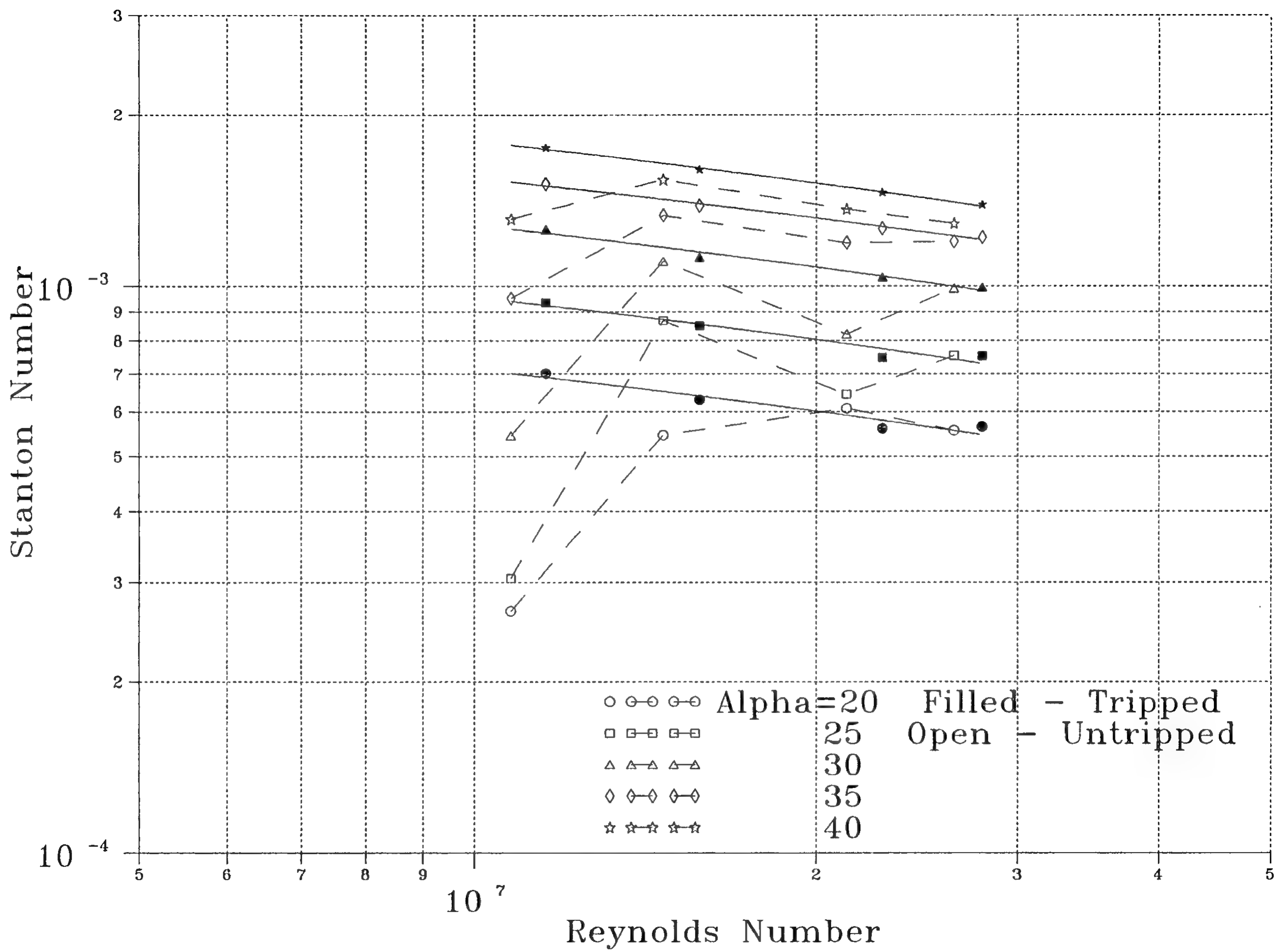


Figure 15b Stanton vs. Reynolds number correlation for Gauge 2

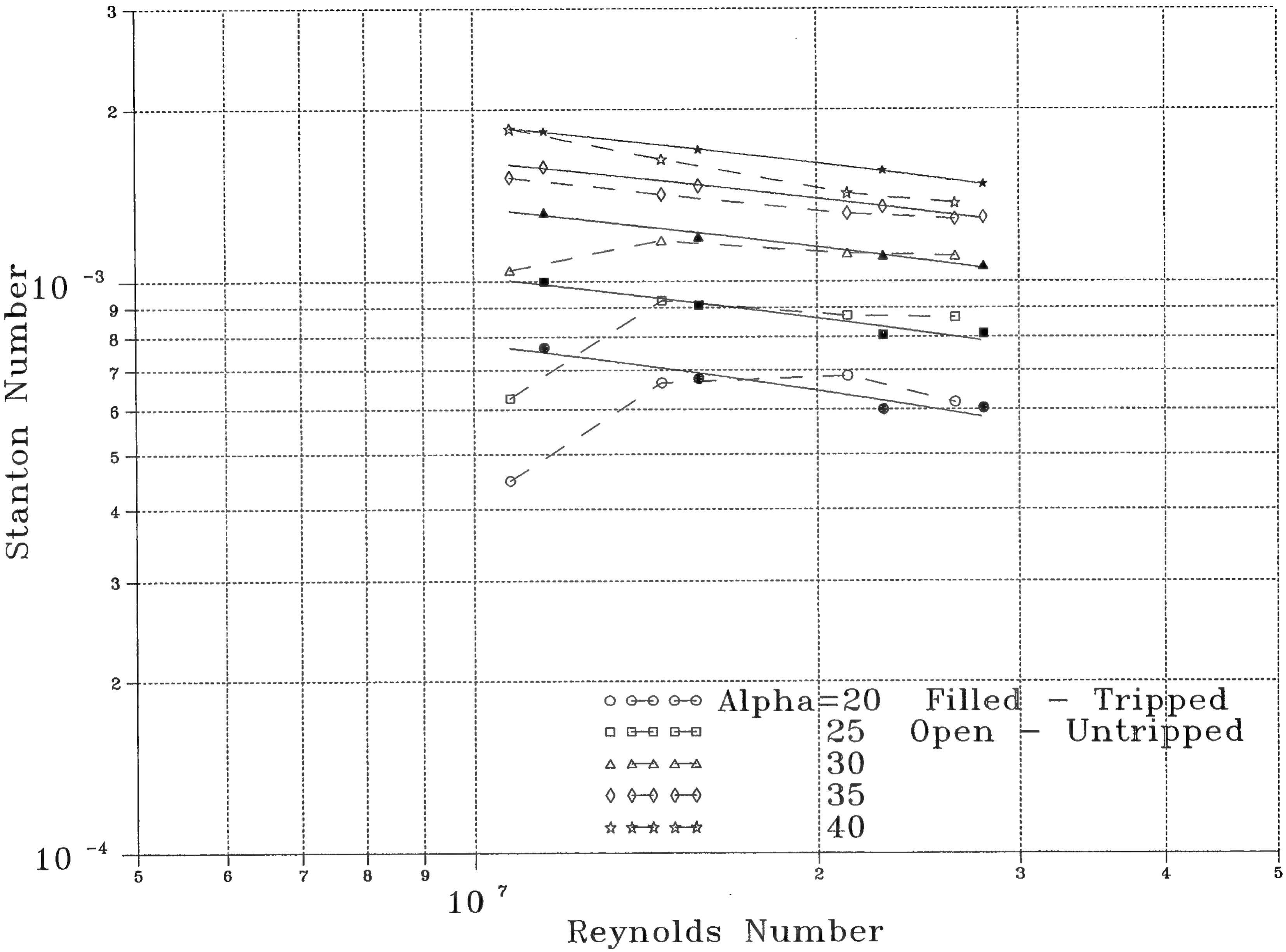


Figure 15c Stanton vs. Reynolds number correlation for Gauge 3

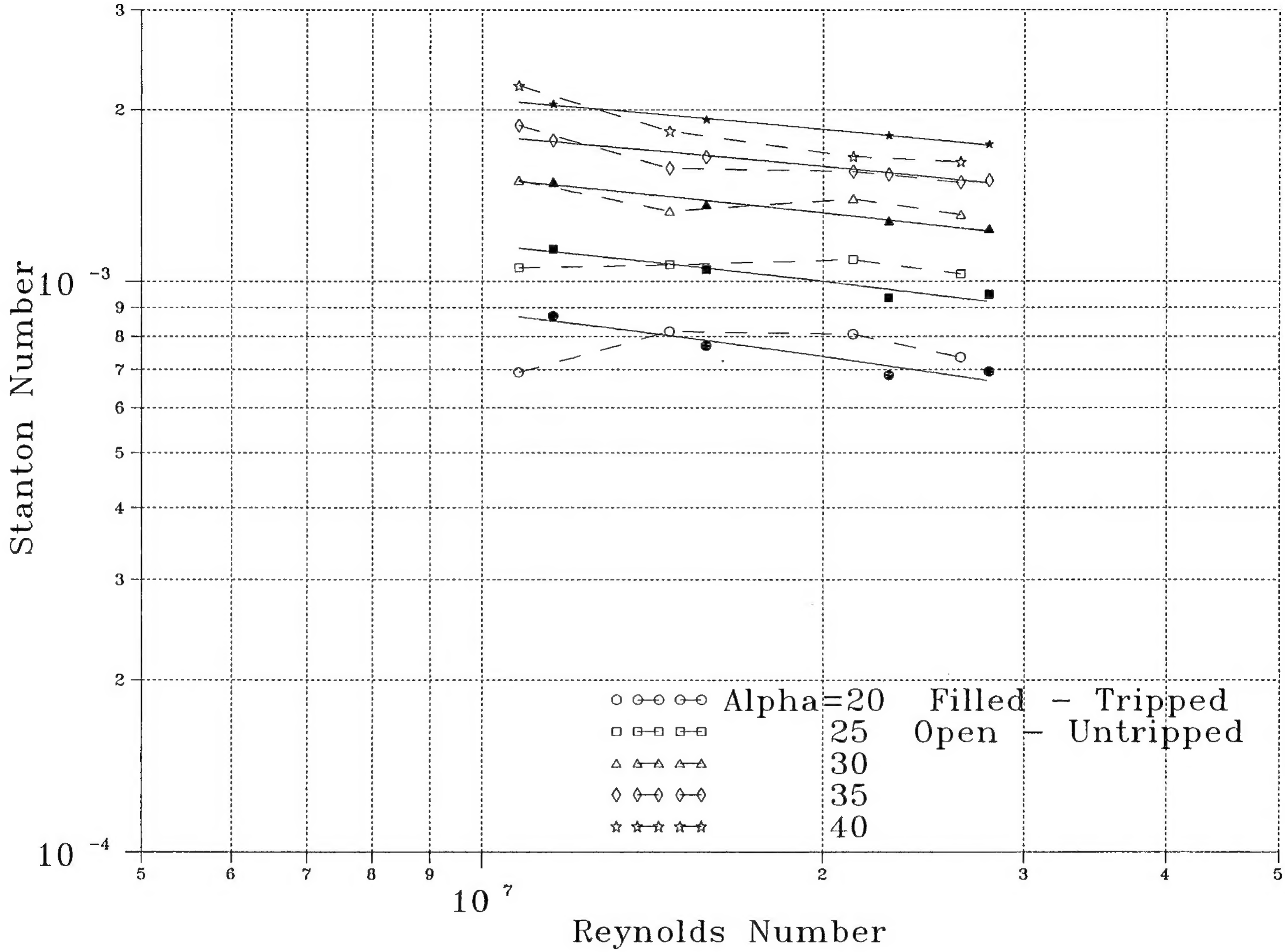


Figure 15d Stanton vs. Reynolds number correlation for Gauge 4

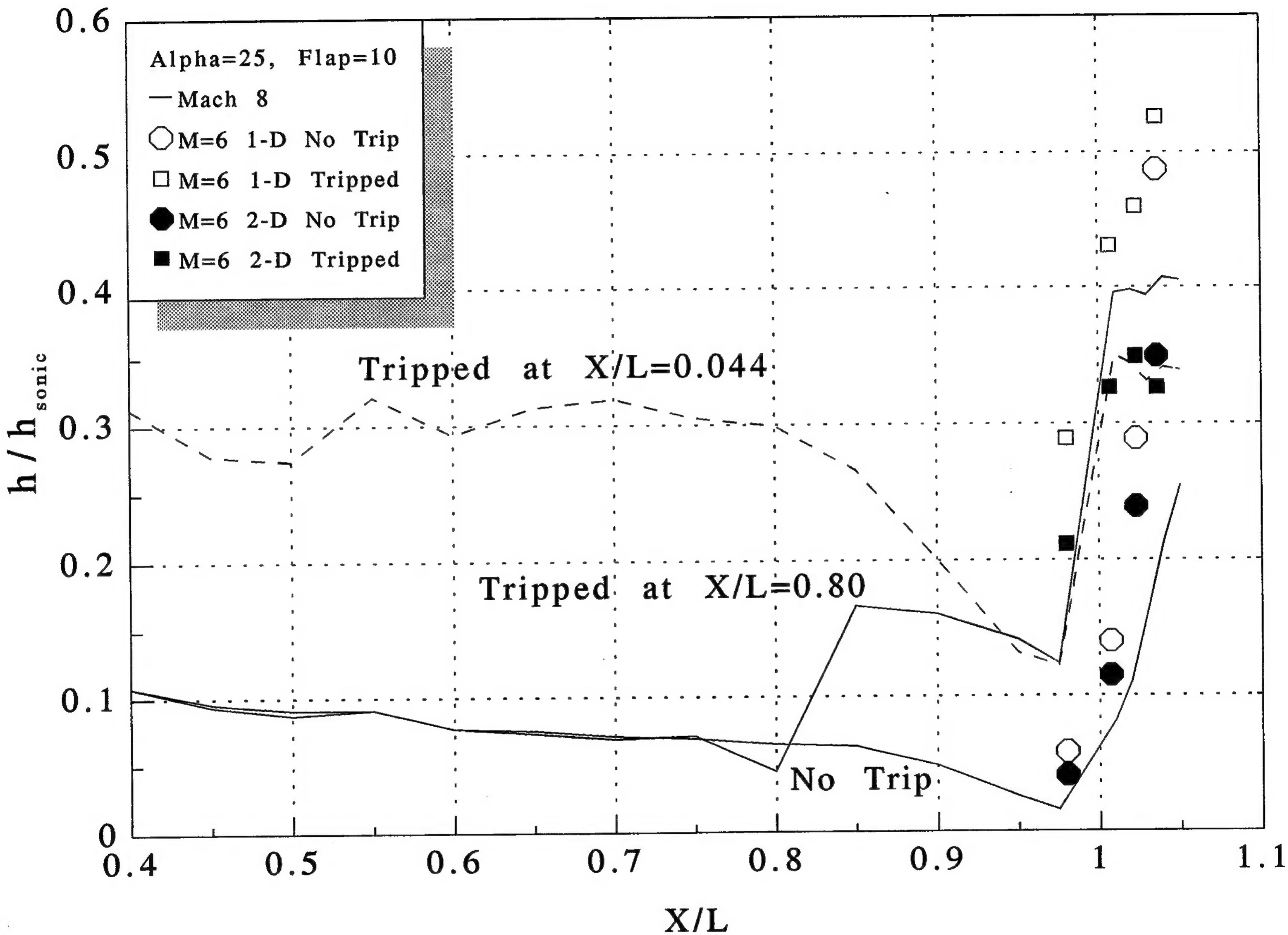


Figure 16 Comparison of small to large scale model test data

This demonstrates another problem which is inherent in small scale models. The normal assumption of 1-D conduction at the gauge locations which forms the basis of standard data reduction techniques is hard to maintain in small scale models. The data may have to be reduced with 2-D techniques which are considerably less efficient from a man-hour perspective.

5.0 Conclusions

A procedure for generating surface coordinates for a wind tunnel model was established along with the data format and transmittal requirements for sending the data to the 4950 TW CAD/CAM system. This capability allows small scale wind tunnel models to be fabricated from the same data base used to generate the geometry files for numerical flow field codes. The models are suitable for testing in the WL Mach 6 High Reynolds Number Facility and produce length Reynolds numbers equal to or greater than that obtained on larger scale models designed for the AEDC VKF Tunnel B.

Miniature coaxial thermocouples were demonstrated to give satisfactory results for heat transfer testing with these small scale models. The small scale of the models did, however, present some problems for data reduction related to multidimensional heat conduction in the model wall. A two-dimensional finite element data reduction technique was required making the data reduction process more difficult than usual.

6.0 References

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4. Beck, James V. and Tu, John S., "IHCP2D: Computer Program for Solutions of General Two-Dimensional Inverse Heat Conduction Problems" AFWAL-TR-88-3111, March 1988.